# USE OF THE CRASH PREVENTION BOUNDARY METHODOLOGY TO DESCRIBE THE PERFORMANCE OF ADAPTIVE CRUISE CONTROL SYSTEMS

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## ABSTRACT

This paper presents a preliminary exploration of approaches to using experimental data for estimating the safety impact of advanced technology systems. The Crash Prevention Boundary (CPB) methodology is the basis for these new approaches. The CPB is an analytical technique to distinguish between driver performance that prevents a crash and performance that results in a crash. In this paper the CPB concept is used to describe the performance of an Adaptive Cruise Control (ACC) systems. Data from the Automotive Collision Avoidance System (ACAS) field operational test of an ACC system is used. This study explores a method to rate safety performance of ACC systems in two situations; where the host vehicle is overtaking a slower moving vehicle and where the host is following a lead-vehicle that is decelerating.

The paper presents an empirically based discussion of new computational procedures that can lead to improved estimates of the safety impact of driver assistance systems. The purpose of this paper is not to do a complete analysis of results from this test; but rather, to use a convenience-sample as a means of exploring new approaches to analyzing the data. The paper compares existing descriptions of safety boundaries with new approaches that are based on the CPB concept. Based on the ACC, it appears that these new approaches have the potential of improving the utility of such data for estimation of the safety impact of driver assistance systems.

## INTRODUCTION

As advanced technology systems have an impact on crash prevention, it will be necessary to develop new analysis tools to help assess the safety impact of the systems. The crash prevention boundary (CPB) methodology is one such technique. This paper uses adaptive cruise control (ACC) system as an example of how the CPB methodology can be used.

The underlying principle behind the CPB concept is that drivers make choices each time they are presented with a situation that may lead to a crash; e.g. catching up to a slower moving vehicle. This choice includes when to take action and how aggressive the action should be; e.g. when to brake and how hard to brake. The consequence of these choices is that in each case the driver either does or does not avoid a crash.

The CPB methodology provides a means of describing the minimum performance that will avoid a crash in each specific situation. The CPB methodology also provides a quantitative means of describing the closeness to a crash that results from a specific performance choice. This closeness, called the Estimated Closest Approach (ECA) can be used to describe an individual driver's performance, or it can be used in the aggregate to describe changes in driver performance, that results from introduction of a driver assistance system, or other type of system that interacts with the driver.

This paper uses a convenience-sample of driving performance from a recently completed field operational test (FOT). The FOT used vehicles that were equipped with a rear-end crash warning system in combination with an adaptive cruise control (ACC) system. The purpose of this paper is not to do a complete analysis of results from this test; but rather, to use this convenience-sample as a means of exploring new approaches to analyzing the data. A complete analysis will be performed by the Volpe National Transportation Systems Center; and results will be published later this year.

This paper is divided into four additional sections. The first section briefly discusses the background, including the concept of the CPB and its role in understanding driver performance in situations that have the potential of evolving into a crash, the computational procedures for reducing experimental data, and a short description of adaptive cruise control systems and the data used in this study. The second section discusses analysis of data; for a subset of data where a following-vehicle overtakes a slower moving lead-vehicle and for a subset of data involving decelerating lead-vehicles. The third section presents several safety contexts for the analysis, including new techniques that are part of the CPB methodology and application of the results to assessment of safety benefits. A fourth, and final, section summarizes the material in the paper.

## BACKGROUND

### Crash Prevention Boundary

The Crash Prevention Boundary (CPB) methodology is an analytical technique to distinguish between driver performance that prevents a crash and driver performance that does not prevent a crash. The foundation of the method – first introduced by Burgett and Miller [3] – is the premise that, for the purpose of understanding driver crash prevention performance, vehicle braking may be described by a constant deceleration profile.

A CPB is an analytical means of describing driver performance in situations that might result in a crash. Figures 1 and 2 are examples, respectively, of CPB curves for situations where the lead-vehicle is traveling at a constant velocity and the lead-vehicle is decelerating. In Figure 1, the driver's performance is described by the time-to-collision (TTC) when effective braking begins and the level of braking. The CPB curve range rate separates this two-dimensional description of driver performance into regions that prevent crashes (to the right of the curve) and regions where driver performance does not prevent a crash (to the left of the curve).

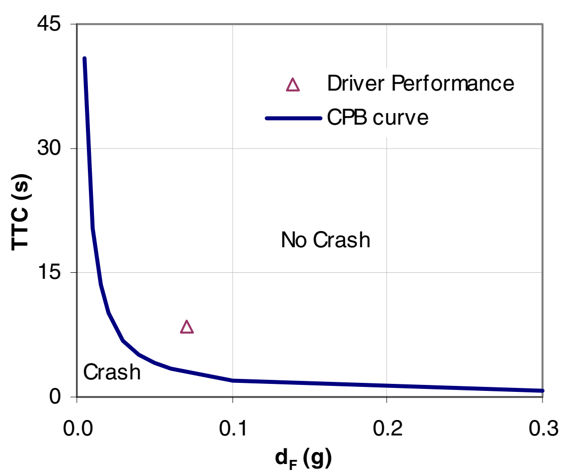


**Figure 1. Example Of A Crash Prevention Boundary, Lead-vehicle At Constant Velocity.**

In the example shown in Figure 2, the CPB curve corresponds to a situation with initial conditions of : both vehicles traveling at 29m/s, with a distance between them (range) of 55.4 m and the lead-vehicle decelerating at 0.4g. The crash prevention performance of the following-vehicle is described by the two parameters; the time at which effective following-vehicle braking begins and the level of braking that the driver chooses. As is described in more detail later in this paper, this parametric description of driver performance is obtained by calculating a "best-fit" approximation of the braking profile of the following driver during the event.

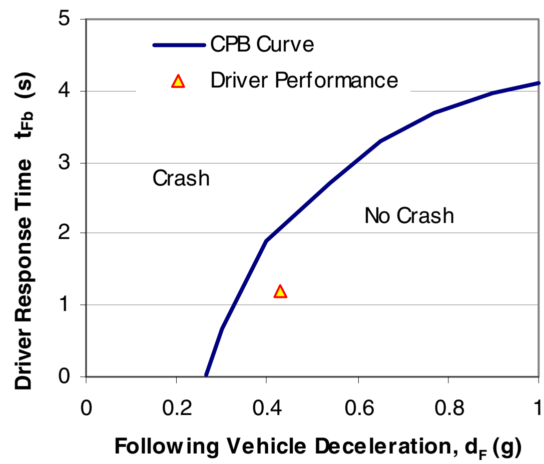


**Figure 2. Example Of A Crash Prevention Boundary, Lead-vehicle Decelerating.**

An extension of the CPB methodology is to estimate how close a driver might have come to a collision during the event. It can be shown that the value of closest approach of the two vehicles that would have occurred if the driver had applied the "best-fit" level of deceleration throughout the event called the estimated closest approach (ECA) is directly related to the closeness of the values of this pair of parameters to the CPB curve.

### Computation Of Empirical Data

Characterization of an ACC braking event is based on the principle of minimization of an measure of error between experimental response data and approximations based on assumed descriptions of the response [2, 4]. The assumed description consists of the starting time for deceleration of both the lead-vehicle and the following-vehicle as well as the level of deceleration for each. Both decelerations are assumed to be constant for the duration that they are applied by the driver. The error measure consists of the following summation of differences between experimental and approximations of speed of both vehicles and range between them.

$$\sum_{t=0}^{t=s}\left(\frac{\left(V_F^{approx}-V_F^{test}\right)^2}{V_F^{test}}+\frac{\left(V_L^{approx}-V_L^{test}\right)^2}{V_L^{test}}+\frac{\left(R^{approx}-R^{test}\right)^2}{\left(R^{test}\right)^3}\right)$$
.

Resulting velocities and displacement that result from the deceleration profiles that minimize this error measure are used for the analysis described in this paper.

Figure 3 is an example showing the deceleration trajectories of an Intelligent Cruise Control (ICC) [7] decelerating event. Deceleration in ICC was achieved by down shifting rather than braking. In this example the lead-vehicle is traveling at a constant velocity. $d_F^{test}$ and $d_L^{test}$ denote actual test deceleration trajectories for the following and the lead-vehicle respectively. Also seen in the plot are the respective best-fit decelerations, which minimize the error measure.

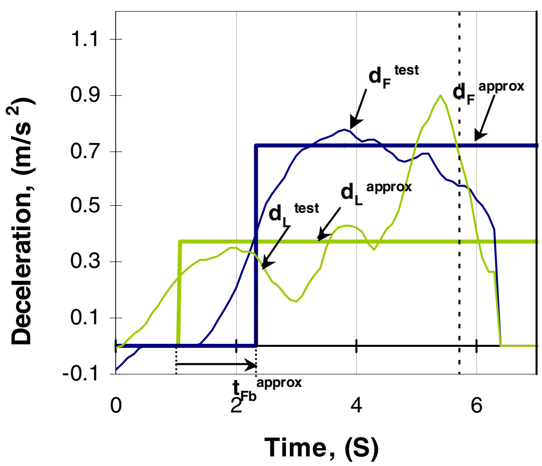


**Figure 3. Deceleration Of Lead And Following Vehicle, Experiment And Best-Fit.**

A comparison of the trajectory of range vs. range-rate of the experimental and its corresponding approximate trajectory is shown in Figure 4. This figure also introduces the concept of estimated closest approach (ECA). This is the closest distance the following vehicle would approach the lead-vehicle, based on the best-fit deceleration profiles.

## Description Of ACC System And Data

The ACC subsystem is a complete control system that uses on board radar to detect objects in front of the vehicle, and provide throttle and brake control to maintain a safe distance to the vehicle ahead. When active, the ACC has two modes, maintain the set speed and maintain the selected headway. In maintaining headway, the system is capable of slowing the vehicle to the speed of

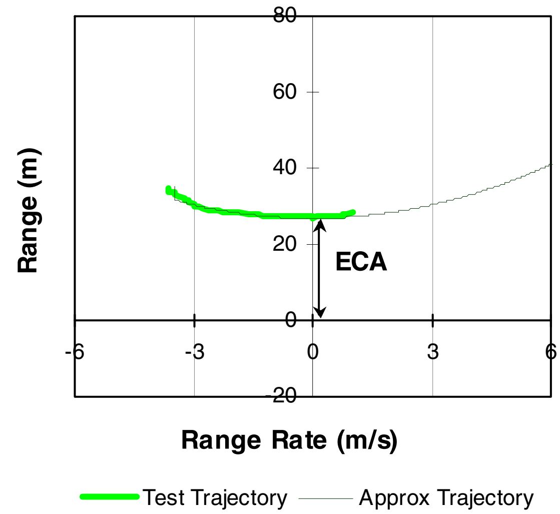


**Figure 4. Experimental And Approximate trajectories in Range/Range-rate coordinates.**

lead-vehicle that is traveling slower than the set speed

The Field Operation Test (FOT) of the Automotive Collision Avoidance System (ACAS) had the following features [1].

- Ten ACC equipped 2002 Buick LeSabres.
- Participants use vehicles as personal vehicle for 4 weeks unsupervised and unrestricted.
- 96 total participants.
- Participants grouped in 20-30, 40-50,and 60-70 age groups and split by gender.
- Over 500 data channels were recorded.
- 137,000 miles driven by the subjects during the FOT.

Operational description of ACAS ACC system;

- Headway, range from 1 to 2 second with 0.2-second increment.
- Maximum deceleration level of 0.3g.
- ACC does not react to stationary objects

In order to understand the ACC brake process, a 2 second span of ACC brake action is essential. Hence only data sets with 2 seconds or more of ACC braking are considered. Data one second before and after ACC braking was examined to understand the dynamics that lead to ACC braking.

## Convenience sample

Driving data from the 10 drivers in the convenience sample included ACC initiated brake control in 670 events. The ACC brake control event time span range varied from a few tenths of a second to six or seven seconds. Of these, only 130 events were used in the analysis. The rest either had a short time span of ACC brake (less than 2 seconds), were involved a cut-in situation, or were involved in a lead-vehicle acceleration situation.

## ANALYSIS OF DATA

### Overtaking at Constant Speed Subset

This section discusses analysis of the data for cases where the subject vehicle, i.e. the host vehicle of the ACC system, is catching up to a slower moving vehicle. At some point the ACC system recognizes the disparity in speed and chooses to decelerate the host vehicle to the speed of the lead-vehicle. This idealized process is described graphically in Figure 5. The diagram shows the path, in range/range-rate coordinates, of motion between the two vehicles as the following vehicle overtakes the lead-vehicle. At some point (denoted by the letter A) the ACC system in the following (host) vehicle chooses to reduce speed to match that of the lead-vehicle. The host vehicle then decelerates to a zero range-rate and begins to follow the lead-vehicle at a fixed distance. The headway setting that the driver of the host vehicle has selected and the speed of the lead-vehicle determine the value of the fixed-distance.

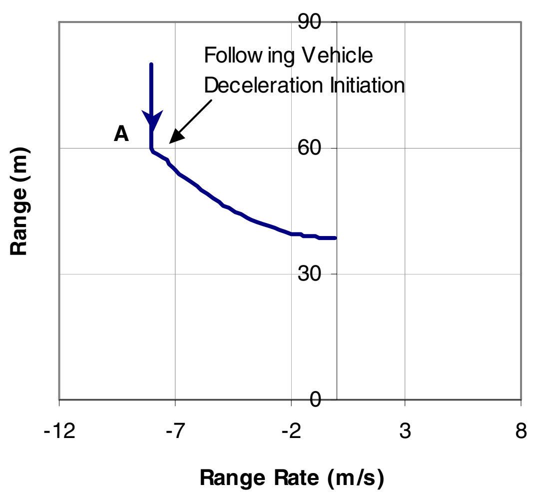


**Figure 5. Range / Range-rate Plot Of An Ideal ACC Braking When Lead-vehicle Is Traveling At Constant Speed.**

In practice, the ACC system performs as a closed-loop control system. The control algorithm, as shown in Figure 6 [7], initiates deceleration or acceleration as a function of the values of range and range-rate relative to an idealized path shown by the diagonal line through the final value of range. The slope of this line and the allowable smallest value of range are design parameters of the control system. In practice, the path of motion in the range/range-rate coordinates is a spiral as shown in Figure 6.

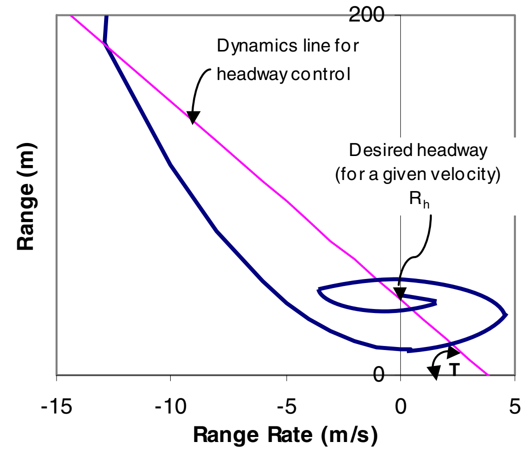


**Figure 6. ACC Overtaking A Slower Vehicle**

A well-designed ACC system should be able to manage most situations where one vehicle overtakes a slower moving vehicle. Thus, it is expected that the data from this FOT would reflect a safe and comfortable reaction to these situations. This intuitive expectation is confirmed by the following discussion of ACC response in overtaking situations.

There are many studies in the literature of how to describe various levels of safety. In this paper, two recent approaches are used and discussed, keeping in mind that the purpose of this paper is to develop procedures more than it is to do a thorough analysis of safety impact. One approach describes regions of the range/range-rate space by the level of safety that those regions represent [5].

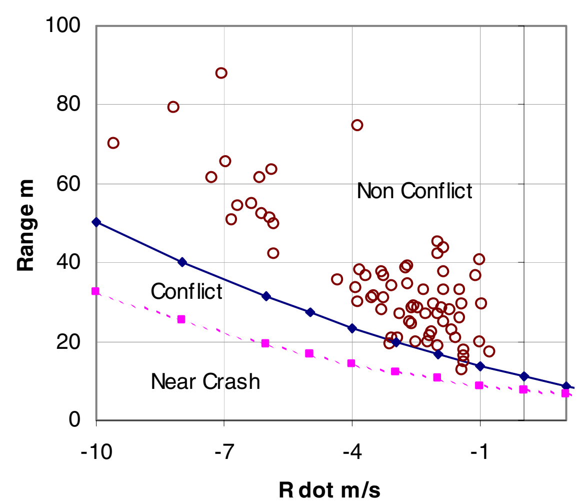


**Figure 7. Braking Response At Constant Speed Scenarios.**

Figure 7 shows curves that describe the estimated level of risk. An event with initial braking conditions that are above the top curve is considered to be a "non-conflict", an event with initial braking conditions between the two curves is considered to be a "conflict", and an event with initial braking conditions below the bottom curve is considered to be near-crashes. Data for the conditions when the following vehicle ACC begins to brake ($t_{Fb}$ Figure-3) are overlaid on these curves. As expected, most of the ACC braking scenarios are in the "non-conflict" region, with a few in the "conflict" region. None of them are in the "near-crash" region.

The second approach uses driver attributes to subdivide the normalized (lead vehicle speed) range/range-rate space into safety-relevant subsets [7]. This classification scheme quantifies driving styles at highway speeds. One of these driving styles is "fast and close". An event with initial braking conditions in the highlighted area reflect a close and/or fast driving style. An overlay of the ACC data shows that the performance of the ACC does not coincide with driver performance that would be considered close and fast.

These two approaches have a common feature that they characterize the safety of response by the conditions that exist at the beginning of the action to resolve an impending conflict.

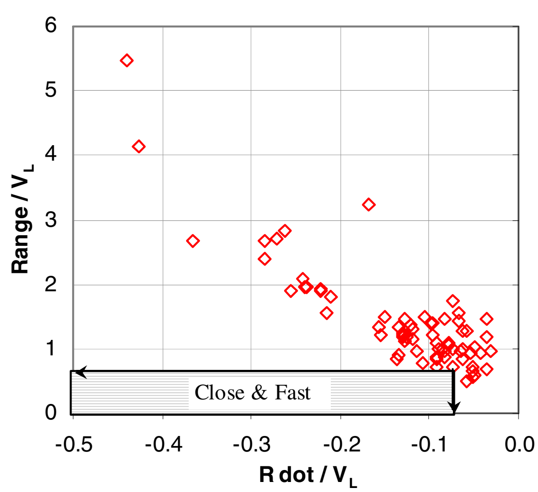


**Figure 8. Driving Style Boundaries, ACC Data**

The two approaches in the discussion above are complemented by two approaches that make use of the Crash Prevention Boundary (CPB) concept. The advantage of the CPB approach is that it is tied directly to the response to a pending conflict rather than being limited to the conditions that exist at the beginning of the response. The first of these CPB approaches uses the distribution of Estimated Closest Approach as the means of assessing the level of safety . The frequency and cumulative distribution for the ACC data is shown in Figure 9. These distributions can be compared with baseline driving to provide a measure of the level safety of the ACC system. Baseline data have not yet been analyzed and the ACC data is only a convenience sample. Therefore the comparison of distributions cannot be made at this time.

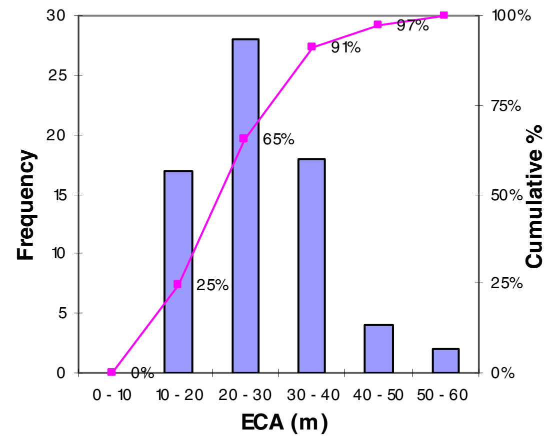


**Figure 9. Distribution of Estimated Closest Approach (ECA).**

The second approach combines ECA and estimated level of braking ($d_F$) as the means of assessing the level of safety. the values of these two parameters for the ACC data are presented in Figure 10. The logic behind this approach is that either a high level of deceleration or a close approach to the lead vehicle is indicative of a less safe condition than if both of them were smaller. This hypothesis has not been studied, so no threshold values exist at this time, although ECA=10 m and $d_F$ =0.3g are shown for demonstration of the approach only.

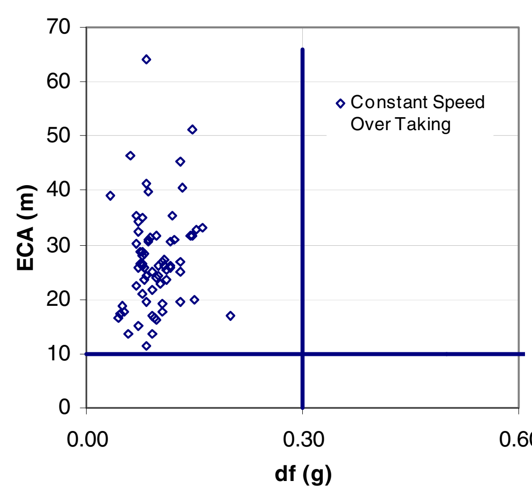


**Figure 10. Estimated Closest Approach Vs Level Of Deceleration By The Following Vehicle.**

**Decelerating Lead-vehicle Subset**

This section analyzes the data for cases where the subject vehicle, i.e. the host vehicle of the ACC system, is initially following another vehicle when the lead-vehicle begins to brake. When the ACC system recognizes the lead-vehicle deceleration it commands an appropriate deceleration by the host vehicle. A graphical depiction of an idealized example is shown in Figure 11.

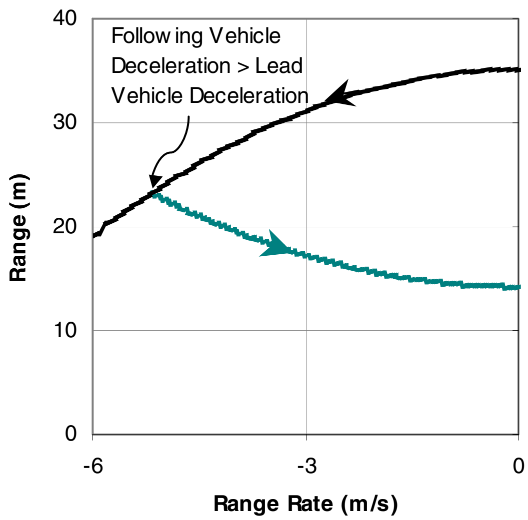


**Figure 11. Range / Range-rate Plot Of Ideal ACC Braking When Lead-vehicle Is Braking.**

The diagram shows the path, in range/range-rate coordinates, of motion between the two vehicles as the lead-vehicle begins to decelerate which causes a negative range-rate and consequent reduction in range. As the host vehicle begins to decelerate, the range-rate becomes less negative and the two vehicles eventually resume travel at the equal speeds. In practice, the closed-loop control of the ACC system performs similarly to its performance in overtaking a slower vehicle, as described above.

One feature of ACC system design is that there is limited deceleration authority. Thus, if the lead-vehicle deceleration is larger than that authority, it will not be possible for the ACC system to completely manage the situation and the driver will have to intervene. Drivers may also intervene if they are not comfortable with the levels of range and range-rate created by the ACC. Thus, it is expected that the data from this FOT would reflect a safe and comfortable reaction to most lead-vehicle situations and that there would be driver intervention in a limited number of cases. This intuitive expectation is confirmed by the following analysis of ACC response in the lead-vehicle deceleration situations experienced in this convenience sample of the FOT.

The two approaches to characterizing the level of safety that were discussed in the preceding section are also applicable to lead-vehicle deceleration situations. Figure 12 describes regions of the range/range-rate space by the level of safety that those regions represent [6]. An event with initial braking conditions that are above the top curve is considered to be a "non-conflict", an event with initial braking conditions between the two curves is considered to be a "conflict", and an event with initial braking conditions below the bottom curve is considered to be near-crashes. Data for the conditions when the following vehicle ACC begins to brake ($t_{Fb}$ Figure-3) are overlaid on these curves. As expected, most of the ACC braking scenarios are in the "non-conflict" region, with a few in the "conflict" region. None of them are in the "near-crash" region

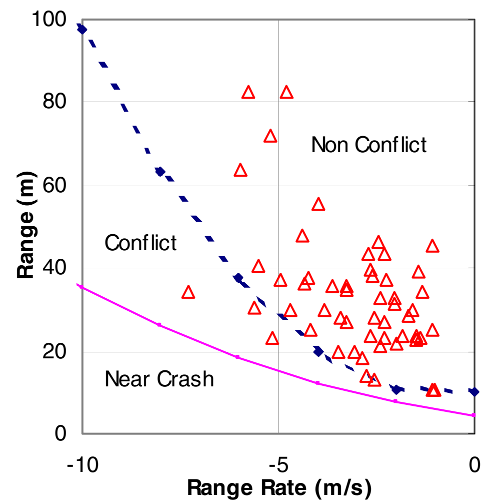


**Figure 12. Braking Response In Decelerating Lead-vehicle**

The second approach shown in Figure 13 uses driver attributes to subdivide the normalized (lead vehicle speed) range/range-rate space into safety-relevant subsets [7]. This classification scheme quantifies driving styles at highway speeds. One of these driving styles is " close". A event with initial barking conditions in the highlighted reflect a close fast driving style. An overlay of the ACC data shows that the performance of the ACC in most of the cases does not coincide with driver performance that would be considered close. On thorough examination of the ACC cases that were in the close region reviled revealed that they were either a cut in or a lane change, which resulted in required deceleration levels greater than the ACC threshold of 0.3g.

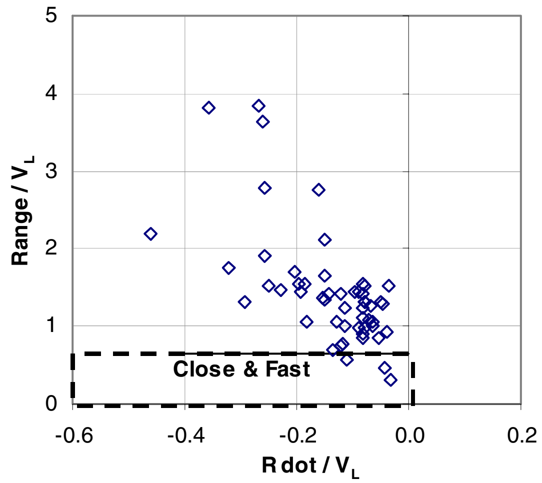


**Figure 13. Driving Style Boundaries, ACC Data**

Similarly, the two methods of analyzing data using the CPB methods are discussed, the first uses the distribution of Estimated Closest Approach as the means of assessing the level of safety and the second approach considers both the Estimated Closest Approach and the level of braking as the means of assessing the level of safety, these are shown in Figures 14 and 15.

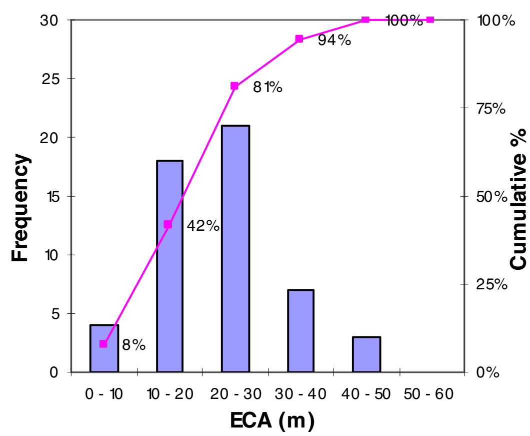


**Figure 14. Distribution Of Estimated Closest Approach (ECA).**

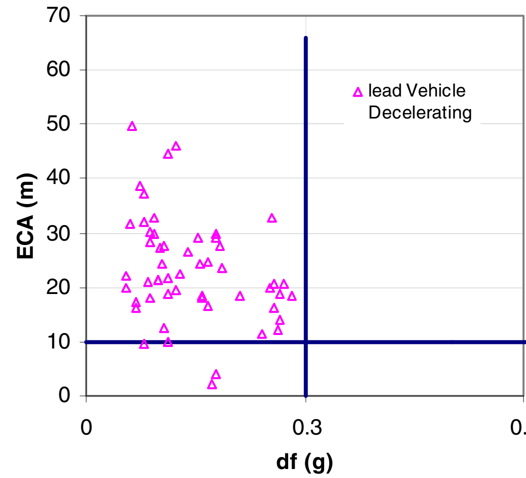


**Figure15 Estimated Closest Approach Vs Level Of Deceleration Of The Following Vehicle.**

A comparison of Figures 14 and 15 with corresponding figures for the overtaking situations shows that the ACC system allows smaller values of ECA and uses higher levels of deceleration than it did for the overtaking cases. However, there is no indication that performance of the ACC system is not adequate or is unsafe for the levels of lead-vehicle decelerations that were experienced in this set of data.

## APPLICATIONS AND ASSESSMENT OF BENEFITS

This section pulls together the data analysis and safety concepts from the preceding sections. The underlying purpose for analyses such as those discussed in this paper is the assessment of the safety impact of driver assistance systems. Many of these same approaches can also be used to address the safety impact of technologies that produce distraction or excessive driver inattention. A standard expression that incorporates all of the elements for producing a quantitative assessment of safety impact is the following equation [8]

$$B = N_{wo} \times \sum_i P_{wo}(S_i \mid C) \times [1 - \frac{P_w(C \mid S_i) \times P_w(S_i)}{P_{wo}(C \mid S_i) \times P_{wo}(S_i)}]$$

In this expression, the subscript i corresponds to unique situations and the ratio of $P_w(C|S_i)$ to $P_{wo}(C|S_i)$ is termed the prevention ratio. It describes the relative likelihood of a crash in a specific situation with and without the driver assistance system. Thus, estimation of this ratio is a key step in making an assessment of safety. The following discussion proposes one approach to obtaining an estimate of this ratio.

It was seen in the preceding sections that the distribution of Estimated Closest Approach provides a quantitative description of the safety performance of a system. In this paper the system is the ACC that was used in the FOT. In the preceding sections, the performance was subdivided into two conditions, overtaking at constant speed and reacting to deceleration of a lead-vehicle. The cumulative distributions of ECA for both types of event are shown in Figure 16.

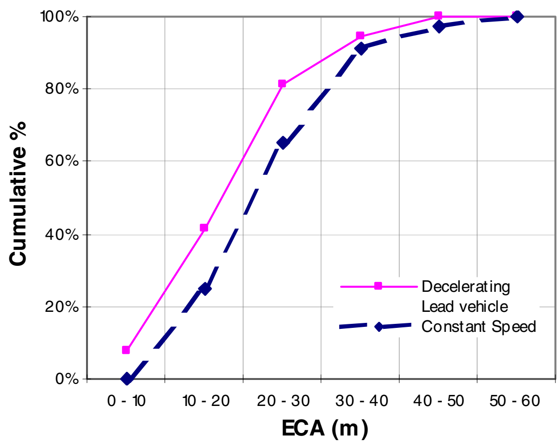


**Figure 16. Comparison Of Cumulative Distribution Of ECA For Two Types Of Events.**

One way to characterize the relative position of the two distributions is to use the value of ECA for a specific percentile for the distribution. For example, if 25 percentile is used, the corresponding values of ECA are 9 m and 14 m, respectively for the decelerating lead-vehicle and overtaking conditions. These values of ECA can then be used as surrogates in the calculation of prevention ratios. It should be noted that the corresponding distributions for driver performance without the assistance of the ACC are not available, so calculation of prevention ratios is not possible at this time. It should also be noted that this use of values of ECA is hypothetical and has not been tested or verified.

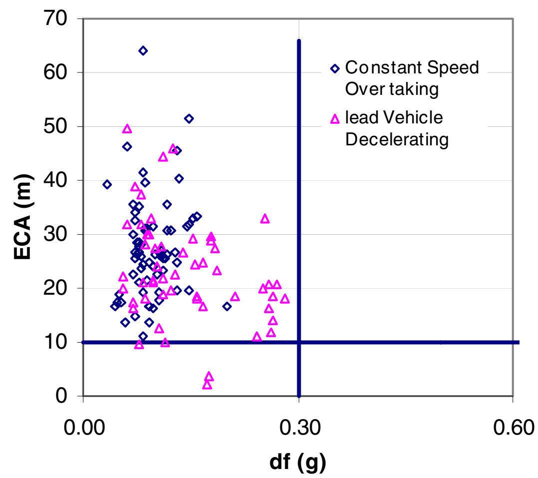


**Figure 17. Summary Of ECA And $d_f$ Data.**

A variation on this approach is the recognition that if short values are combined with high levels of host vehicle deceleration, it is a good indication that the situation resulted in a near-crash. This recognition can be quantified by separating system response data into the four quadrants shown in Figure 17. If appropriate values are assigned to the edges of the quadrants, e.g. 0.3 g and 10 meters, the percentage of responses that fall in the lower right quadrant is an indication of the level of safety of the driving experience. In this case, the values in the lower right quadrant for baseline and assisted conditions would be used to compute the prevention ratio.

## SUMMARY

This paper has presented an empirically based discussion of new computational procedures that can lead to improved estimates of the safety impact of driver assistance systems. An Adaptive Cruise Control system that was tested in a field operational test is the basis for the discussion. The purpose of this paper is not to do a complete analysis of results from this test; but rather, to use a convenience-sample as a means of exploring new approaches to analyzing the data. The paper compares existing descriptions of safety boundaries with new approaches that are based on the Crash Prevention Boundary concept. Based on the data from use of adaptive control system it appears that these new approaches have the potential of improving the utility of such data for estimation of the safety impact of driver assistance systems.

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